Clarification of algae-laden water using electrochemical processes

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Abstract

Algae contamination of surface water and drinking water supplies is a significant problem particularly in rural areas. A decentralized inexpensive technology that would effectively remove algae from water would be beneficial. Electrocoagulation (EC) combined with electroflotation (EF) as a single process (ECF) is a promising algae harvesting technique with no moving parts that may be powered using a modest array of photovoltaic panels if a low power system can be developed. Here, an ECF system was constructed to study the energy required to remove algae from a simulated drinking water supply. Results from 18 ECF experiments indicated a >95% improvement of water clarity measured by optical density (OD_{750}) could be achieved with as little energy as 1.25 kWh m^{-3}. The key was to find the ideal combination of gas bubbles produced by EF (G) and coagulant from the EC relative to the concentration of suspended solids (S). The ideal gas to solids (G/S) ratio for the ECF system ranged from 0.09 to 0.17. In solutions containing chloride (Cl^-) ions ECF produced chlorine gas which is known to contribute to disinfection. Results suggest that ECF can efficiently remove algae and simultaneously contribute to disinfecting contaminated drinking water supplies.

Keywords: Algae, electrocoagulation, electroflotation, drinking water, disinfection

Introduction

The World Health Organization estimates that more than 80% of the nearly 1 billion people lacking access to clean drinking water are located in rural areas (WHO and UNICEF, 2008). In many of these areas, the problem stems from inadequate wastewater treatment and other sources of surface water pollution that are responsible for water-borne illnesses, which cause millions of deaths annually (Grant et al., 2012). While these problems can be solved by centralized water treatment and distribution systems, this approach is not practical for most rural areas, which lack both the infrastructure and capital to build and support such systems (Mollah et al., 2004). In rural areas, algal growth due to eutrophication is a major contributor to water contamination (Shen et al, 2011; El-Dars et al., 2015) and an efficient way to remove algae would be an important step in the direction of improving water quality.

It is well established that algae can be removed from suspension using flotation techniques that typically combine coagulating agents with bubbles (Green et al., 1996; Wiley et al., 2009). The coagulants form algae aggregates that adhere to rising bubbles, causing them to float. While effective, many flotation techniques require a constant supply of expensive chemical coagulants

1

and energy-intensive compressed gas systems to operate, making them poorly suited for rural areas (Wiley et al., 2011).

Electrocoagulation (EC) combined with electroflotation (EF) as a single process (ECF) is a relatively inexpensive technique shown to be effective in removing algae and a wide range of pollutants from water (Feng et al., 2003; Emamjomeh and Sivakumar, 2009; Azarian et al., 2007; Goa et al., 2011; Sires and Brillas, 2012). The EC process generates coagulants and metal hydroxides that destabilize and aggregate suspended particles *in situ*, through the electrochemical dissolution of soluble electrodes (Jiang et al. 2002). Previous research has shown that EC requires lower coagulant dose, reduces sludge production, is less pH sensitive, and removes turbidity with higher efficiency than conventional chemical coagulation (Abuzaid et al. 2002; Han et al. 2002; Goa et al. 2010). The EF portion of the system generates hydrogen and oxygen gas bubbles by the electrolysis of water. As these gas bubbles rise through the water column, they attach to aggregated particles and transport them to the surface, producing clear subnatant. A combined ECF system is a promising approach to remove algae from contaminated water in rural areas because it has no moving parts, requires only electricity as an input, and can be powered completely with photovoltaic modules (Mollah et al. 2001; Rodriguez et al. 2007).

It is also known that if chloride (Cl^-) is present in the bulk solution the ECF process can produce chlorine gas, which acts as a disinfectant (Hernlem and Tsai, 2000; Abuzaid et al., 2002). This combination of clarifying and disinfecting contaminated water suggests ECF would be beneficial in rural areas, particularly because it requires little maintenance. The key will be developing effective ECF systems that require as little electricity as possible to operate (Mollah et al., 2001; Rodriguez et al. 2007).

Here we evaluated the energy requirements of ECF for 95% algae removal, determined the gas to solids (G/S) ratio and monitored the, pH, temperature and conductivity. We compared calculated coagulant dose using Faraday's law with the actual experimental dose required. We determined conditions for the greatest treatment efficiency with minimal power consumption.

Methods

Algae Cultivation
An algae cultivation system was constructed from a 1,000-liter plastic container cut in half to improve solar exposure. Two diffusers at the bottom of the container were aerated continuously to control oxygen and provide mixing. The system was filled with tertiary wastewater effluent from the Santa Paula Water Recycling Facility (Santa Paula, CA, USA). No attempt was made to maintain axenic conditions, but the system was inoculated with *Chlorella vulgaris* (UTEX 2714; University Texas Culture Collection; Austin, TX, USA). The dissolved oxygen, which remained near saturation level, and pH were measured using Sensorex submersible electrodes (S8000 and DO6442-T; Garden Grove, CA, USA). A DL-06 programmable logic controller (PLC) (Automation Direct, Cumming, GA, USA) activated a mass flow controller (Aalborg, Orangeburg, NY, USA) that injected CO_2 at a rate of 5 l min^{-1} to maintain the culture pH between 7.5 and 7.7. Ammonia-nitrogen (NH_3-N) and nitrate-nitrogen (NO_3-N) were monitored using a Hach (Loveland, CO, USA) DR2800 Spectrophotometer. Approximately 30 grams of

urea-nitrogen fertilizer (46-0-0) was periodically added to the 400 l culture when the combined concentration of NH_3-N and NO_3-N was <5 mgl^{-1}.

Electrocoagulation and Electroflotation (ECF) System
The combined ECF system used aluminum electrodes for EC and non-soluble iridium oxide coated (20 g m^{-2} coating density) titanium (Ti/IrO$_2$) electrodes for EF operated independently to increase the longevity of the soluble aluminum electrodes and optimize bubble production for flotation.   The ECF system was tested in 18 experimental trials, using different current settings
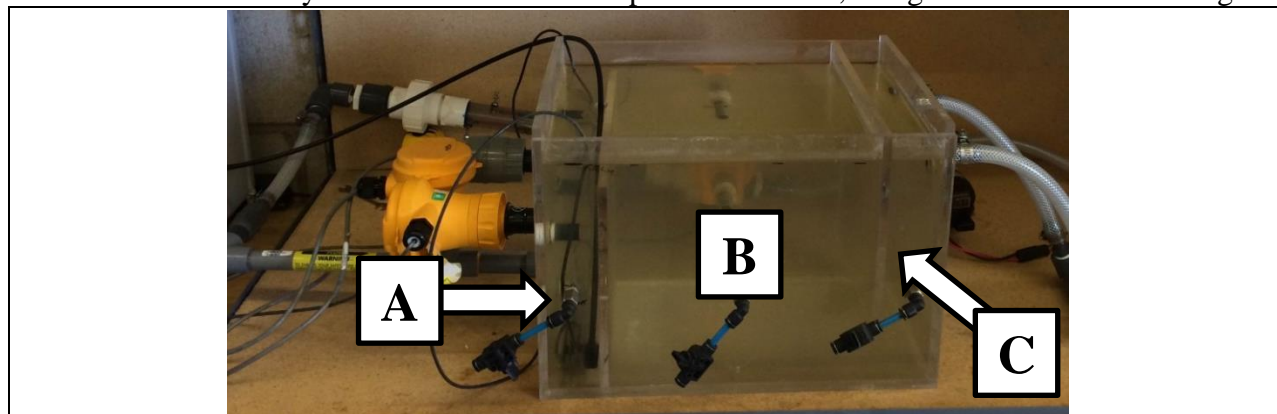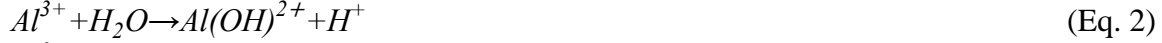

Figure 1. The ECF vessel with instrumentation installed during leak testing. The coagulation zone (A), flotation zone (B) and underflow zone (C) are separated with baffles. The tubing on the exit of the underflow zone is connected to a recirculation pump that feeds back into the bottom of the coagulation zone. The valves on each of the zones are for sample collection.

to determine the most efficient coagulant dose and gas production for flotation. The ECF vessel was constructed from 9.5 mm thick sheets of clear acrylic plastic (30 cm wide x 40 cm long x 28 cm deep). The interior of the vessel was separated into three zones: (1) the coagulation zone with two aluminum electrodes (20.3 cm x 2.5 cm x 0.32 cm) held together with non-conductive 5 mm plastic spacers, (2) the flotation zone with four Ti/IrO$_2$ electrodes (25.4 cm x 1.3 cm x 0.20 cm) wired in parallel with 5 mm plastic spacers, and (3) the underflow zone, which permitted clear subnatant to recirculate to the coagulation zone using a pump (model 2088-343-170 12 VDC diaphragm pump, SHURflo, Costa Mesa, CA, USA) (**Figure 1**). The speed of the pump was adjusted by varying the voltage of a HY1520EX DC power supply (VOLTEQ, San Jose, CA, USA). Two independently controlled Y030LX2400 DC power supplies (Acopian, Eastman, PA, USA) operated in constant current mode delivered the power to each of the electrode assemblies.

A model 2537 paddlewheel flow meter (GF Signet, Schaffhausen, Switzerland) measured the recirculation rate through the system. Temperature and pH electrodes (GF Signet, model 2750) were mounted in the coagulation zone and a conductivity sensor (GF Signet, model 2850) was mounted in the flotation zone. Data from the sensors were transmitted to a custom human-machine interface (HMI) designed using Lookout Direct Software (Automation Direct, Cumming, GA, USA) with a DL06 PLC. The HMI was used to start and stop and ECF power supplies at user-specified current set-points and to log data.

The sacrificial aluminum EC electrodes released ions into solution when direct current (DC) was applied to the anode (Eq.1). Several monomeric species with different coagulation properties are produced when the aluminum generated by EC is released into solution (Eq. 1 – Eq. 5).

$$Al \rightarrow Al^{3+} + 3e^-$$ (Eq. 1)
$$Al^{3+} + H_2O \rightarrow Al(OH)^{2+} + H^+$$ (Eq. 2)
$$Al^{3+} + 2H_2O \rightarrow Al(OH)_2^+ + 2H^+$$ (Eq. 3)
$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$$ (Eq. 4)
$$Al^{3+} + 4H_2O \rightarrow Al(OH)_4^- + 4H^+$$ (Eq. 5)

The total amount of aluminum dissolved into solution (coagulant dose) is related to the current applied to the electrodes by Faraday's Law (Eq. 6).

$$w = \frac{ItM}{zF}$$ (Eq. 6)

Where,
w = Mass of aluminum dissolved into solution, g;
I = Current applied to the electrodes, Amperes;
t = Time, seconds;
M = Molecular weight of aluminum, g mol^{-1};
z = Number of electrons involved in the redox reaction;
F = Faraday's constant, 96,485 C mol^{-1}

Hydrogen and oxygen bubbles are produced during this process at the anode (Eq. 7) and cathode (Eq. 8), respectively, comprise the EF component of the harvesting system.

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$ (Eq. 7)
$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$ (Eq. 8)

Four 20-minute trials using different amperage settings (0.75, 1.75, 2.75 and 3.75) were performed to determine the dissolution rates of the aluminum EC electrodes. The electrodes were submerged in a 1,000 ml graduated cylinder containing distilled water mixed with NaCl to increase the conductivity to approximately 2000 µs cm^{-1}. Every 5 minutes electrodes were removed, dried in an oven at 104° C for 10 minutes, placed in a desiccator to cool for 10 minutes, and weighed with a TE214S analytical balance (Sartorius, Bohemia, NY, USA). The measured weight loss was compared to predictions based on Faraday's Law.

ECF Operation
In the 18 experiments a variety of ECF current combinations were tested to achieve a 95% reduction in algae OD$_{750}$ while minimizing power consumption (**Table 1**). Each trial was conducted using 30 liters of algae culture transferred to the ECF vessel. The solution was continuously circulated through the vessel at approximately 3.5 l min^{-1} for each 30-minute trial. The initial total suspended solids (TSS) concentration, as determined using method 2540D of Standard Methods (American Public Health Association, 1998), and OD$_{750}$ of the algae solution was determined prior to initiating the ECF processes. The OD$_{750}$ was measured on samples

4

collected from the underflow zone in 5-minute intervals. Improvements in water clarity over time relative to initial conditions were then quantified using (Eq. 9).

$$\%_{red} = \frac{OD_{750i} - OD_{750n}}{OD_{750i}} \cdot 100$$ (Eq. 9)

Where,
$\%_{red}$ = % reduction of OD_{750};
OD_{750i} = Initial OD_{750};
OD_{750n} = OD_{750} after n minutes of treatment

Table 1. The current setpoints for ECF during each of the 18 experimental trials.

Trial	EC Current, Amperes	EF Current, Amperes	Trial	EC Current, Amperes	EF Current, Amperes
1	3.75	5.75	10	4.50	3.00
2	6.25	15.3	11	4.50	3.00
3	2.25	3.25	12	6.00	6.00
4	3.75	5.75	13	6.00	9.25
5	5.25	3.00	14	1.00	1.75
6	1.50	12.2	15	2.80	4.25
7	4.50	12.2	16	4.25	6.00
8	1.60	12.2	17	2.25	8.00
9	4.80	12.2	18	4.25	8.25

The mass of gas required to remove a mass of suspended solids, referred to as the gas to solids (G/S) ratio is an important process control metric for any flotation technology. Decreasing G/S ratios indicated more efficient operation, as less power is necessary to remove the solids. As the volume of hydrogen and oxygen generated used for flotation is a function of current applied to the system, the total volume of gas produced by ECF was calculated with (Eq. 10).

$$Q_t = \frac{ItV}{\eta_H F} + \frac{ItV}{\eta_O F}$$ (Eq. 10)

Where,
Q_t = Total gas production rate, $l\ sec^{-1}$;
I = Current applied to the electrodes, Amperes;
V = Molar volume of gas, $22.4\ l\ mol^{-1}$;
F = Faraday's constant, $96,485\ C\ mol^{-1}$;
t = Time, seconds;
η_H = mole of electrons transferred per mole of H_2 produced;
η_O = mole of electrons transferred per mole of O_2 produced

The result of (Eq. 10) can then be converted to mass (Eq. 11 – Eq. 12) and used to determine the G/S ratio (Eq. 13).

$$n = \frac{PV}{RT}$$ (Eq. 11)

Where,
n = mol;

5

P　　= Pressure, atm;
V　　= Volume, l;
R　　= Ideal gas constant, 0.0821 L-atm mol-K^{-1};
T　　= Temperature, K

$$M_T = n_{H_2} \cdot MW_{H_2} + n_{O_2} \cdot MW_{O_2} \qquad \text{(Eq. 12)}$$
　　Where,
　　M_T　= Mass of total gas produced, g;
　　n_{H_2}　= mol of H$_2$;
　　MW_{H_2} = Molecular weight of H$_2$, g;
　　n_{O_2}　= mol of O$_2$;
　　MW_{O_2} = Molecular weight of O$_2$

$$G/S = \frac{M_T}{TSS_i \cdot S_{vol}} \qquad \text{(Eq. 13)}$$
　　Where,
　　G/S　= Gas:Solids ratio;
　　M_T　= Mass of total gas produced, g;
　　TSS_i　= Initial [TSS], g l^{-1};
　　S_{vol}　= System volume, l

The power consumed for each experimental trial was then calculated using (Eq. 14).

$$E = \frac{kW}{t} \cdot \frac{1}{S_{vol}} \qquad \text{(Eq. 14)}$$
　　Where,
　　E　　= Energy consumed, kWh m^{-3}
　　kW　= Power consumption, kW ;
　　t　　= Time, hours
　　S_{vol}　= System volume, m^{-3}

An additional benefit of ECF is that potential exists to generate chlorine gas from Cl$^-$ ions in solution for *in situ* disinfection . As current is applied to the submerged electrodes chlorine gas is generated at the anode, which dissolves in the surrounding solution to form hypochlorite ions (Eq. 15 – Eq. 17).

$$2Cl^- \rightarrow Cl_2 + 2e^- \qquad \text{(Eq. 15)}$$
$$Cl_{2(g)} + H_2O \rightarrow HOCl + H^+ + Cl^- \qquad \text{(Eq. 16)}$$
$$HOCl \leftrightarrow H^+ + OCl^- \qquad \text{(Eq. 17)}$$

The concentration of Cl$^-$ present in the Santa Paula effluent averages 140 ± 10.7 mg l^{-1} (n = 65), suggesting that disinfection by-products are likely to be generated during the ECF process. The total chlorine residual of subnatant following ECF treatment was quantified using Hach method 8167 and a DR890 spectrophotometer.

Results and Discussion

6

The primary goal was to find ECF conditions in which algae were effectively removed from simulated drinking water in a reasonable time with the lowest power consumption. To this end we measured the changes in optical density (OD_{750}) of the system and the amount of current applied to the electrodes submerged in the experimental chamber. The current influenced the quantity of aluminum ions released as coagulant from the aluminum electrode and the amount of gas produced for flotation which is produced at both the aluminum and Ti/IrO_2 electrodes. The challenge in finding the most efficient operation was to determine the current to each electrode
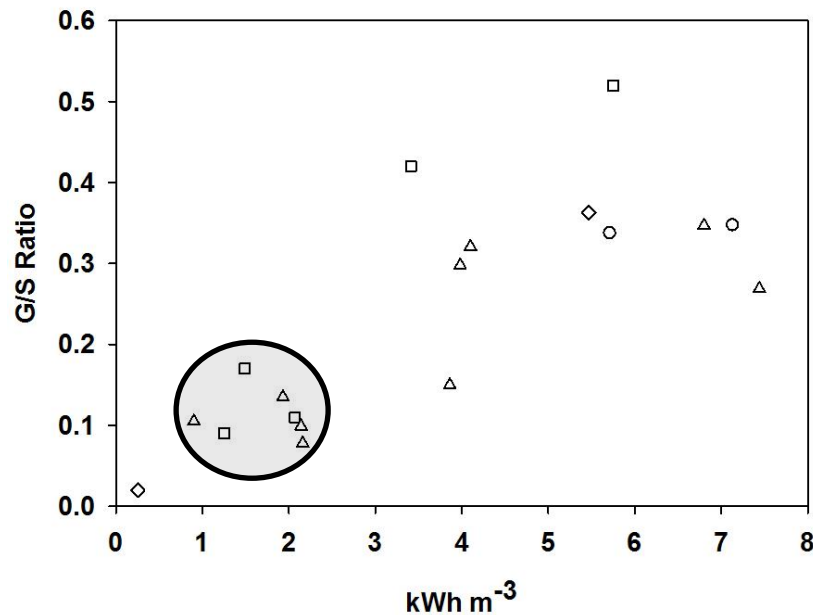

Figure 2. The relationship between G/S ratio, power consumption and treatment efficiency as determined by OD_{750} reduction ($\square = \geq 95\%$, $\blacktriangle = 75 - <95\%$, $\circ = 50 - <75\%$, $\Diamond = <50\%$ reduction in OD_{750}). The wide spread of the data is indicative of mismatch between ideal power for coagulation and optimum bubble production with EF. High removal efficiencies paired with lower power requirements and G/S ratios indicate efficient operation of both ECF systems. The large circle containing a cluster of points signifies experimental trials (n = 7) with optimum G/S ratios. While four of these trials did not meet the target treatment objective of 95% OD_{750} reduction, these data provide insight regarding current setpoints providing most efficient EF operation.

that produces sufficient aluminum coagulant and gas for flotation without applying too much current to aluminum electrode, which erodes. This balance in the current was determined using the gas to solid (G/S) ratio, which compares the mass of the gas produced (G) to the total mass of suspended solids (S) (see eq. 12 & 13 Materials and Methods).

Algae removal and power: To determine the ECF conditions that effectively removed suspended algae with minimal power, the OD_{750} was compared to the G/S ratio with different current settings to the EC and EF electrodes (**Figure 2**). In 18 experiments the OD_{750} reduction ranged from 29.9% to 99.5%, the G/S ratio ranged from 0.01 to 0.52 and power consumption ranged from $0.3 - 7.4$ kWh m^{-3}. Nine of the experiments decreased OD_{750} by 75 to <95%

(**Figure 2, ▲**), had G/S ratios of 0.08 – 0.35, and power requirements ranging from 0.9 – 7.4 kWh m^{-3}. Nine of the ten experiments consuming the most power had the highest G/S ratios (0.27 – 0.54), suggesting too much current was applied to the EF electrodes. The experiment in this group with the lowest G/S ratio (0.15) used an EC current setting of 6.0 amperes, which accounted for the elevated power consumption. In the seven experiments with low G/S ratios (0.08 – 0.17) and low power consumption (0.9 – 2.2 kWh m^{-3}) (**Figure 2, circled lower left**), three had a 95% reduction in OD$_{750}$ indicating that a G/S ratio in this range is adequate for algae
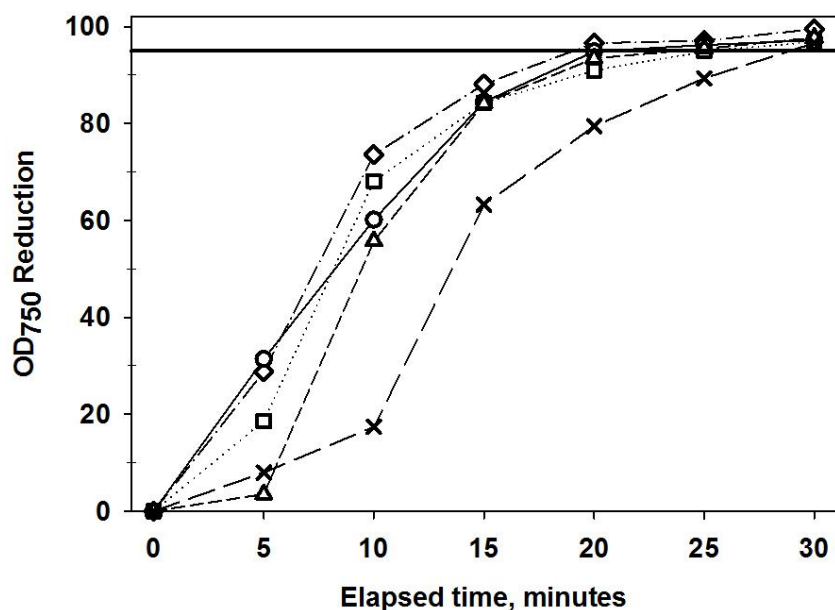

Figure 3. The percent OD$_{750}$ reduction over time for each experiment meeting the treatment objective. The horizontal vertical bar represents the target reduction of 95%. ($\Diamond$ = Experiment 2; $\circ$ = Experiment 4; $\square$ = Experiment 5; **X** = Experiment 15; ▲ = Experiment 18.

removal. The other four experiments had OD$_{750}$ reductions of 80-90%, suggesting the need for a higher coagulant dose.

Experiments 7 and 8 improved the clarity by 58% and 54%, had higher G/S ratios (0.34 and 0.35) and required large amounts of electrical power (7.1 and 5.7 kWh m^{-3}) due to EF overdose (**Figure 2, $\circ$**). The poor removal may be due to inadequate coagulant dose given that the G/S ratio was high. Experiment 6 and 14 had the least reduction in OD$_{750}$ (29.9% and 31.8%) (**Figure 2, $\Diamond$**) due to insufficient coagulant and gas excess in Experiment 6, indicated by the high G/S ratio (0.36) and large power requirement (5.5 kWh m^{-3}) and insufficient coagulant and gas in experiment 14, indicated by the low power used 0.25 kWh m^{-3}.

In five of the 18 experiments algae removal was >95% (**Figure 2, $\square$**) within 30 minutes and in four of the five more than 50% of the algae were removed in the first 10 minutes (**Figure 3**). In two trials (**Figure 3**: **X** and ▲) the rate of removal was initially slow, but rapidly increased after five or ten minutes, presumably when the aluminum coagulant and bubbles had accumulated sufficiently.

8

In experiment 2 (**Figure 3**: ◊) the OD_{750} was reduced by 96.6% after 20 min and 99.5% after 30 min. However, this trial used the most power and had the highest G/S ratio (0.52), indicating there was an excess of bubbles generated than required for effective separation (**Table 2**). Additionally, an aluminum precipitate was observed in the floating algal mat, which suggests an excess of coagulant. Similarly in experiment 18 (**Figure 3**: ▲)   the 95% OD_{750} reduction goal was reached in 25 minutes, but resulted in a high G/S ratio (0.42) due to an excess of EF current and lower solids loading (**Table 2**).

Table 2. The power consumption, G/S ratio and applied current for the experiments with ≥95% reduction in OD_{750}.

Trial	Power Used, $kWh\ m^{-3}$	Total gas produced, mg	TSS, $mg\ l^{-1}$	G/S Ratio	EC Current, Amperes (SD ±)	EF Current Amperes (SD ±)
2	5.75	2414	154	0.52	6.28 (0.03)	15.31 (0.04)
4	1.25	1069	415	0.09	3.80 (0.03)	5.76 (0.03)
5	2.07	1146	362	0.11	5.23 (0.03)	2.97 (0.03)
15	1.49	1086	214	0.17	2.80 (0.03)	4.21 (0.03)
18	3.41	1615	128	0.42	4.28 (0.03)	8.26 (0.03)

In contrast, experiment 4 (**Figure 3**: ○), which reduced the OD_{750} by 95.0% after 20 minutes and 97.2% after 30 minutes, used the least amount of power (1.25 kWh m^{-3}), and had the most favorable G/S ratio (0.09), indicating efficient operation of both ECF components of the system (**Table 2**). Trial 5 had an only slightly higher G/S ratio (0.11), suggesting efficient operation of the EF system, but the overall power consumption was much higher (2.07 kWh m^{-3}) due to the higher current applied to the EC system (**Table 2**).

Experiment 15 (**Figure 3**: **X)** required the entire 30 minutes to meet the OD_{750} reduction goal of 95%, but required only 1.49 kWh m^{-3} of power and had a G/S ratio of 0.17. While this trial was efficient, the additional time needed to achieve the desired separation implies that the coagulation dosing may have been slightly low (**Table 2**).

ECF power consumption and the factors that affect it: The power consumption of the three most efficient experiments ranged from 1.25 and 2.07 kWh m^{-3} and had G/S ratios between 0.09 and 0.17. Experiments consuming the most electrical power had the highest G/S ratios, which demonstrate the importance of this metric when optimizing the efficiency of ECF. The ideal G/S ratio identified here is much lower than the 0.26 – 0.88 previously reported by Wiley et al. (2009) for the removal of algae grown in a wastewater oxidation pond using dissolved air flotation (DAF). The reduced G/S ratio observed with ECF is attributed to smaller bubble diameters that yield higher removal efficiencies (Burns et al., 1997**;** Dimoglo et al., 2004). Goa et al. (2011) reported that ECF power requirements for effective algae removal at the lab scale consume 0.3 kWh m^{-3}. However, additional research is required to determine the scalability of this result.

Identifying the optimum coagulant dose with EC is also needed to optimize the energy efficiency of the ECF system. However, the predictability of coagulant dose using Faraday's Law is highly dependent on the configuration of the EC electrodes. We observed that coagulant dose exceeded

9

theoretical predictions by 109 – 215% when aluminum dissolution rates were measured using electrodes submerged in a 1,000 ml graduated cylinder; values consistent with those reported elsewhere (Dononi et al., 1994; Chen et al., 2000; Calvo et al., 2003). Mouedhen et al. (2008) attributed this deviation from Faraday's Law to chemical dissolution at the cathode (not the anode, which followed the law), and suggested it was due to high pH during hydrogen evolution creating more basic conditions. This discrepancy between actual and theoretical dosing can be alleviated by altering the flow around the electrodes or by using insoluble cathodes, although the

Table 3. The pH, temperature, and conductivity before and after ECF for the experiments with $\geq$95% reduction in OD_{750}.

Trial	Initial pH	Final pH	Initial Temp, °C	Final Temp, °C	Initial Conductivity, μS cm^{-1}	Final Conductivity, μS cm^{-1}
2	8.48	8.18	24.2	28.1	2413	2259
4	5.65	5.78	23.5	24.5	2750	2589
5	8.03	7.98	20.4	22.0	2000	1915
15	8.54	8.21	21.7	23.0	2234	2132
18	8.26	8.04	19.0	21.7	2310	2022

formation of an anode passivation layer would increase resistance and therefore increase power requirements.

Increasing temperature and pH shifts towards neutral were observed during ECF operation (**Table 3**). The shift toward neutral pH is advantageous because it precludes the need for chemical pH adjustment (Ghernaout et al., 2011), but effects coagulation by changing the solubility of aluminum. For example, aluminum solubility is minimal near neutral pH and precipitating aluminum hydroxides provide coagulation in a process known as "sweep flocculation", where suspended particles bind to precipitates and form larger aggregates (Duan and Gregory, 2003). In contrast, the higher temperatures increase solubility, which could inhibit the formation of aluminum hydroxides. This contributes to the difficulties associated with predicting coagulation performance, as these variables could differ greatly between water sources.

The power requirements of the ECF system are strongly influenced by the conductivity of the bulk solution. Higher conductivity is advantageous as it provides less electrical resistance between the electrodes, lessening the voltage required to deliver the desired current. However, it was noted that conductivity of the solution decreased during operation of the ECF system (**Table 3**). This can be explained through the oxidation of ionic compounds to gases that are stripped from solution by hydrogen and oxygen bubbles or to adsorption to aluminum hydroxide. Thus prolonged operation may require increased voltage to overcome increased resistivity, but this can be controlled if small amounts of NaCl are added. The addition of NaCl has the added benefit of forming chlorine gas, which is a disinfectant.

ECF production of chlorine gas as a disinfectant: In water containing Cl^- ions from natural sources or from additions used in water treatment, the ECF system generates chlorine gas that acts as a strong disinfectant (Hernlem and Tsai, 2000). To determine the disinfecting capacity of

the system, we used a spectrophotometer to determine the total chlorine residual of the subnatant following treatment (see materials and methods). The total amount of chlorine generated electrochemically can theoretically be calculated based on the Cl^- concentration and current. However, this does not accurately describe how well the solution is disinfected. For example, if all chlorine generated reacts with dissolved and solids in solution there may not be enough to provide disinfection. The residual is more telling because it indicates that the chlorine has reacted with the solution with excess remaining.
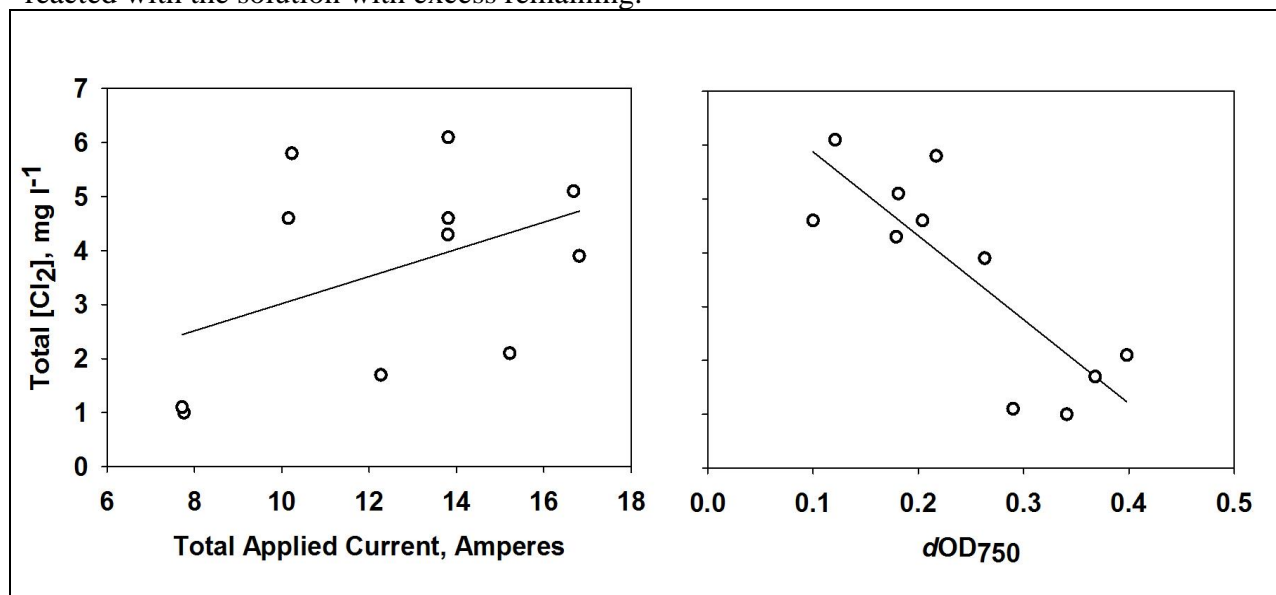

Figure 4. The weak correlation ($r^2 = 0.19$) between chlorine residual and current (Left) and the stronger correlation ($r^2 = 0.68$) between chlorine residual and OD_{750} (Right), support the hypothesis that chlorine is reacting with the suspended solids in solution.

Predicting the current required to produce enough chlorine for adequate disinfection is challenging because it depends on the Cl^- concentration of the source water and the chlorine demand exerted by the solution. For the system described here, there was a poor correlation ($r^2=0.19$) between the total chlorine residual and the total current applied (**Figure 4**). However, a much stronger correlation coefficient ($r^2=0.68$) was observed between the chlorine residual and the change in OD_{750} with time. Less total chlorine residual was detected in experiments with the greatest change in OD_{750}, which suggests that the chlorine produced is reacting with suspended solids. If additional power is required beyond that needed for effective removal of suspended solids, it could be generated using the non-soluble EF electrodes to prevent shortening the utility of the sacrificial aluminum electrodes. A similar approach was adopted by Hernlem and Tsai (2000), who successfully utilized EF for the clarification and disinfection of food process water, reporting strong reductions in the presence *E. coli*. However, a more depth analysis is needed to assess the disinfecting efficiency of the ECF system presented here.

Conclusions
The ECF system effectively removed algae from water with low power requirements under the right combination of conditions. The most successful experiment reduced the OD_{750} by 95% after 20 minutes of treatment and required 1.25 kWh m^{-3} of electricity. The G/S ratio providing effective removal of coagulated algae ranged between 0.09 and 0.17, lower than values reported

for DAF. This results from the smaller diameter and therefore greater surface area of electrochemically generated H_2 and O_2 bubbles. While the power consumption obtained during these experiments is reasonable low, advancements in electrode configuration and containment vessel design could further reduce energy requirements and allow for more accurate predication of coagulant dose. The ECF process has the potential to provide some disinfection through the electrochemical production of chlorine gas. However, the extent of disinfection is dependent on the chlorine demand exerted by the source water and the concentration of Cl^- ions in solution. The low power requirements, effective removal of suspended algae and potential to provide disinfection suggest that development of ECF technology can improve water quality particularly for rural areas with limited resources and problems with contaminating algae.

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13

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